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The Evershed Flow and the Brightness of the Penumbra

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Summary. The Evershed flow is a systematic motion of gas that occurs in the penumbra of all sunspots. Discovered in 1909, it still lacks a satisfactory explanation. We know that the flow is magnetized, often supersonic, and that it shows conspicuous fine structure on spatial scales of $0.2''$–$0.3''$, but its origin remains unclear. The hope is that a good observational understanding of the relation between the flow and the penumbral magnetic field will help us determine its nature. Here I review advances in the characterization of the Evershed flow and sunspot magnetic fields from high-resolution spectroscopic and spectropolarimetric measurements. Using this information as input for 2D heat transfer simulations, it has been demonstrated that hot Evershed upflows along nearly horizontal field lines are capable of explaining one of the most intriguing aspects of sunspots: the surplus brightness of the penumbra relative to the umbra. They also explain the existence of penumbral filaments with dark cores. These results support the idea that the Evershed flow is largely responsible for the transport of energy in the penumbra.

1 Introduction

The Evershed effect was discovered a century ago as a Doppler shift of spectral lines in sunspots away from disk center (Evershed 1909). The shift is to the red in the limb-side penumbra and to the blue in the center-side penumbra, and happens together with strong line asymmetries. (e.g., Stellmacher and Wiehr 1980). Already from the very beginning, these signatures were explained in terms of a nearly horizontal outflow of gas – the Evershed flow. The motions that give rise to the Evershed effect represent the most conspicuous dynamical phenomenon observed in sunspots. Advances in instrumentation have allowed us to characterize them with increasing degree of detail, but their origin remains a fundamental problem in sunspot physics.

Another unsolved problem is the brightness of the penumbra, which radiates about 75% of the quiet Sun flux. This is significantly larger than the 20% emitted by the umbra. In recent years, considerable efforts have been made to understand the energy transport in sunspots. Jahn and Schmidt

(1994) proposed convection by interchange of magnetic flux tubes as the process that heats the penumbra, and Schlichenmaier et al. (1998) developed the moving tube model to simulate it. This mechanism was later found to be unable to explain the brightness of the penumbra (Solanki and Rüedi 2003; Schlichenmaier and Solanki 2003), but the moving tube model survived as a reasonably good, yet idealized, description of the penumbral magnetic field.

In the photosphere, the penumbra is a conglomerate of nearly horizontal field lines embedded in a stronger and more vertical field, as first proposed by Solanki and Montavon (1993) in their uncombed model. Strong gradients or discontinuities of the atmospheric parameters occur along the line of sight due to the vertical interlacing of different magnetic components. This characteristic organization of the field explains many features of the penumbra, including its filamentary appearance in continuum intensity and polarized light (see Schlichenmaier 2003; Bellot Rubio 2007; Borrero 2009, Schlichenmaier 2009; and Tritschler 2009 for reviews).

The Evershed flow occurs along the more horizontal field lines and is a global phenomenon, so it represents an excellent candidate to heat the penumbra. Based on the radiative cooling times of hot plasma embedded in a non-stratified atmosphere, Schlichenmaier and Solanki (2003) concluded that the Evershed flow would be able to provide the required amount of energy if the penumbral field lines return to the solar surface soon after they emerge into the photosphere. At that time, the existence of such field lines was unclear and many considered this result as a serious difficulty for the otherwise successful uncombed model.

The direct detection of small patches of magnetic fields diving back below the solar surface everywhere in the mid and outer penumbra (Ichimoto et al. 2007a; Sainz Dalda and Bellot Rubio 2008) removes this problem. Also, the radiative cooling times in a stratified atmosphere which is continuously heated by the Evershed flow may be quite different from those estimated by Schlichenmaier et al. (1999). With longer cooling times, a single flow channel would be able to heat larger penumbral areas than previously thought. These two considerations call for a re-examination of the Evershed flow as the mechanism responsible for the brightness of the penumbra.

Here I summarize the properties of the Evershed flow as deduced from high-resolution spectroscopic and spectropolarimetric measurements (Section 2). Any serious attempt to model the energy transport in the penumbra has to include this information. Ruiz Cobo and Bellot Rubio (2008) used it to solve the heat transfer equation in a stratified atmosphere consisting of hot Evershed flows along nearly horizontal magnetic flux tubes. The calculations indicate that the tubes would be observed as bright penumbral filaments with a central dark lane. The filaments are heated by the flow over a length of about 3000 km; together with their surroundings, they emit 50% of the the quiet Sun intensity. These results suggest that the surplus brightness of the penumbra is a natural consequence of the Evershed flow (Section 3). Another mechanism proposed to explain the brightness of the penumbra is overturning convection

(Section 4). However, this idea will remain speculative until measurements at $0.1''$ demonstrate the existence of convective motions in penumbral filaments.

2 The Evershed Flow at High Spatial Resolution

Most of what we know about the Evershed flow has been learned from high-resolution filtergrams and spectropolarimetric measurements at $1''$–$2''$ (see Tritschler 2009, and references therein). Despite their moderate angular resolution, the latter have resulted in a very detailed characterization of the flow thanks to its relation with the more inclined fields of the penumbra, which allows inversion techniques to separate the different magnetic atmospheres that coexist in the pixel.

With the advent of instruments capable of reaching $0.3''$, most notably the Universal Birefringent Filter at the Dunn Solar Telescope, the TRIPPEL spectrograph at the Swedish Solar Telescope, and the spectropolarimeter of the Solar Optical Telescope aboard Hinode, the results derived from Stokes inversions have been confirmed and often extended in a more direct way. As a consequence we now have a rather good understanding of the Evershed flow. In the next paragraphs I will discuss the properties of the flow at high spatial resolution and its relation with the magnetic field of the penumbra based on these observations.

The Evershed Flow Occurs in the Dark Cores of Penumbral Filaments

Bright filaments in the inner penumbra consist of a central dark core surrounded by two lateral brightenings (Scharmer et al. 2002; Sütterlin et al. 2004). The distance between the lateral brightenings is typically 100 km, but in some cases it may be as large as 300 km, making these structures easy targets for 50 cm telescopes.

Bellot Rubio et al. (2005) performed spectroscopy of dark-cored penumbral filaments with the Swedish Solar Telescope. They used the TRIPPEL spectrograph to observe the Fe I 557.6 nm and 709.0 nm lines at a resolution of $0.2''$. A bisector analysis of the data revealed that the Evershed flow is stronger in the dark cores, although the lateral brightenings also show non-negligible velocities. The velocities were found to increase with depth in the photosphere. The observed variation of the Doppler shift with position in the penumbra and heliocentric angle indicated that the Evershed flow is directed *upward* in the inner penumbra. Also, the Zeeman splitting of the Fe II 614.9 nm line was consistent with slightly weaker fields in the dark cores as compared with the lateral brightenings or the surrounding medium.

The observation that the Evershed flow occurs preferentially in the dark cores of penumbral filaments has been confirmed by Langhans et al. (2005, 2007), Rimmele and Marino (2006), and Rimmele (2008) using high-resolution

filtergrams. The Fe I 630.25 nm magnetograms of Langhans et al. (2005) and van Noort and Rouppe van der Voort (2008) show the dark cores with weaker signals than the bright edges, suggesting more inclined fields. The field could also be weaker, but no definite conclusion can be made because of possible saturation effects (in the strong field regime, the amplitude of the circular polarization signal does not increase with the field strength). Interestingly, these measurements do not show negative polarities across the filaments, that is, the field in the dark cores and the lateral brightenings appears to have the same orientation (but see the remarks by Sánchez Almeida 2009). A similar conclusion has been reached by Bellot Rubio et al. (2007) from an analysis of Hinode spectropolarimetric measurements: the inclination of the magnetic field is slightly larger in the dark cores, but no change of polarity occurs with respect to the surroundings (at least at a resolution of $0.3''$).

An intriguing feature revealed by high-resolution Dopplergrams (Hirzberger & Kneer 2001; Rouppe van der Voort 2002; Bellot Rubio et al. 2006) and spectropolarimetric measurements (Bellot Rubio et al. 2004; Ichimoto et al. 2008) is that there is no place in the penumbra where the velocities drop to zero, except where they should vanish because of projection effects. For example, in the inner penumbra the stronger flows occur in the bright filaments, but smaller velocities are also seen in between them. The origin of these motions remains unexplained.

The Evershed Flow Returns to the Solar Surface in the Middle Penumbra and Beyond

The large-scale geometry of the flow can be inferred from the azimuthal variation of the line-of-sight (LOS) velocity as a function of radial distance. The results of this analysis indicate that, on average, the flow is slightly inclined upward in the inner penumbra, then becomes horizontal at about 0.8 penumbral radii, and finally returns to the solar surface in the middle and outer penumbra with inclinations of $10°$–$30°$ to the horizontal (Schlichenmaier and Schmidt 2000; Bellot Rubio et al. 2003; Tritschler et al. 2004; Bellot Rubio et al. 2006, and references therein). This must be understood as an average behavior; of course, upflows also exist in the outer penumbra, but the downflows dominate the azimuthal average.

On smaller scales, Rimmele and Marino (2006) employed Fe I 557.6 nm filtergrams taken at the Dunn Solar Telescope to demonstrate that the Evershed flow emerges as a hot upflow in bright penumbral grains and quickly becomes horizontal along individual filaments. This result has been confirmed by Ichimoto et al. (2007a), who had the ingenious idea of using Stokes V maps in the far wings of Fe I 630.25 nm to identify strongly blueshifted or redshifted polarization signals. Figure 1 shows two such magnetograms for AR 10973 at -27.7 pm and $+27.7$ pm from line center, as observed by Hinode on 1 May 2007. The heliocentric angle of the spot was $6°$. The signs have been reversed in the red-wing magnetogram so that black indicates the same

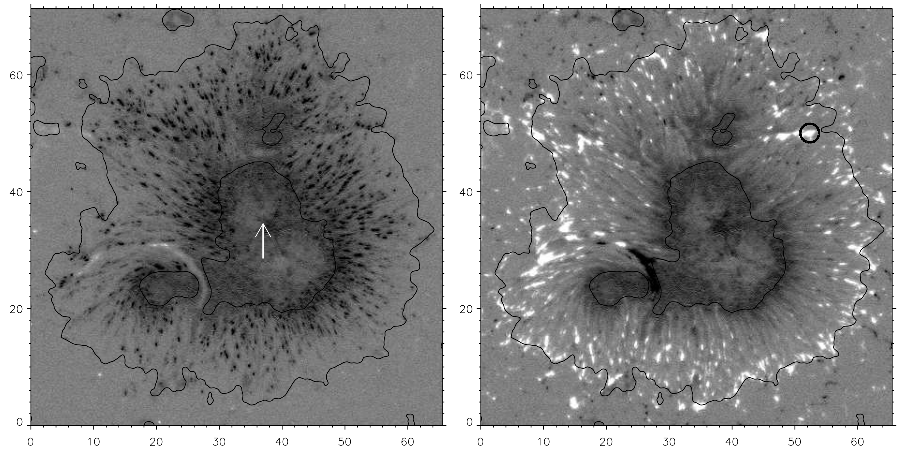

Fig. 1. Stokes V maps of AR 10973 at -27.7 pm (*left*) and $+27.7$ pm (*right*) from the center of the Fe I 630.25 nm line. The data were taken by the Hinode spectropolarimeter on 1 May 2007, with the spot at a heliocentric angle of 6°. *Black* represents the polarity of the spot in the two maps. The *circle* overplotted in the *right* panel marks the downflowing patch considered in Fig. 2. Distances are given in arcsec, and the *arrow* points to disk center.

polarity in the two panels. The structures visible in Fig. 1 represent strongly Doppler-shifted polarization signals. However, the strength of the signal does not inform about the velocity itself, as it also depends on other parameters such as the field inclination or the gas temperature.

Figure 1 shows with unprecedented clarity the sources and sinks of the Evershed flow (for additional information, see the paper by Ichimoto 2009). The blue wing magnetogram is dominated by small patches of strong upflows located preferentially (but not exclusively) in the inner penumbra. The red wing magnetogram shows similar patches of downflows scattered all over the middle and outer penumbra. Strong downflows occur in the inner penumbra too, but they are less frequent. Westendorp Plaza et al. (1997) were the first to detect downflows in the penumbra, near the sunspot edge. The polarity of the magnetic signals in the downflowing patches is opposite to that of the spot. Thus, not only the flow, but also the magnetic field, returns to the solar surface. Observed at lower spatial resolution, this pattern of upflows/downflows would result in the average radial behavior mentioned above.

The flow field revealed by the Hinode magnetograms is highly organized. Presumably each upflow in the inner penumbra connects with a downflow in the mid or outer penumbra, although this needs to be verified by studying the evolution of the flow. The patches are larger than the angular resolution of the Hinode spectropolarimeter ($0.3''$), suggesting that they are resolved structures. Moreover, the downflows occur intermittently, not in every pixel as indicated by the inversions of Sánchez Almeida (2005). This is consistent

with the idea that the Evershed flow is confined to discrete channels oriented radially; the far-wing magnetograms only show the relatively vertical inner and outer footpoints of these structures. The channels seem to be shorter than the width of the penumbra, although it is likely that their lengths vary as they evolve with time.

The Evershed Flow is Often Supersonic

The Evershed flow attains the largest velocities in the outer penumbra. Spectropolarimetry at $1''$ has shown that the azimuthally averaged flow is nearly supersonic from the middle penumbra outward (Bellot Rubio et al. 2004). There have been reports of strongly Doppler-shifted line satellites in the penumbra (Wiehr 1995), and numerical models of the Evershed flow also predict supersonic velocities (Montesinos and Thomas 1997; Schlichenmaier et al. 1998). However, these velocities have not been detected directly until the advent of Hinode.

Figure 2 displays the Stokes spectra observed in one of the downflowing patches of Fig. 1 and a nearby pixel used as a reference (solid and dotted lines, respectively). The spectra represented by the solid lines are remarkable in a number of ways. To start with, the intensity profiles exhibit a very bright continuum and strongly tilted red wings. The tilt is maximum near the continuum, indicating that the flow velocity increases with depth in the atmosphere. The Stokes V profiles are normal and have two lobes. However, they are redshifted as a whole by 19.5 pm or $\sim$9 km s^{-1}. This LOS velocity is smaller than the true velocity because of projection effects, but it already exceeds the sound speed. The clear signatures of supersonic velocities in the spectra recorded by Hinode are a consequence of the high spatial resolution, which makes it possible to separate the flow channels from their surroundings.

In general, the downflowing patches observed in the middle and outer penumbra exhibit anomalous Stokes V profiles with three lobes (Fig. 3). They can be interpreted as the superposition of two regular signals. One of them has the polarity of the spot and is relatively unshifted, while the other has opposite polarity and shows a very strong redshift. The two signals do not necessarily come from different atmospheres in the pixel; at the resolution of Hinode, it is more likely that they are produced by two magnetic components stacked along the line of sight. We know that this configuration must exist in the penumbra because the observed Stokes V profiles have nonzero area asymmetries. The inversions of Jurčák et al. (2007) also demonstrate that models with strong gradients in the vertical direction are able to reproduce the complex profiles measured by Hinode without any horizontal interlacing of different magnetic components.

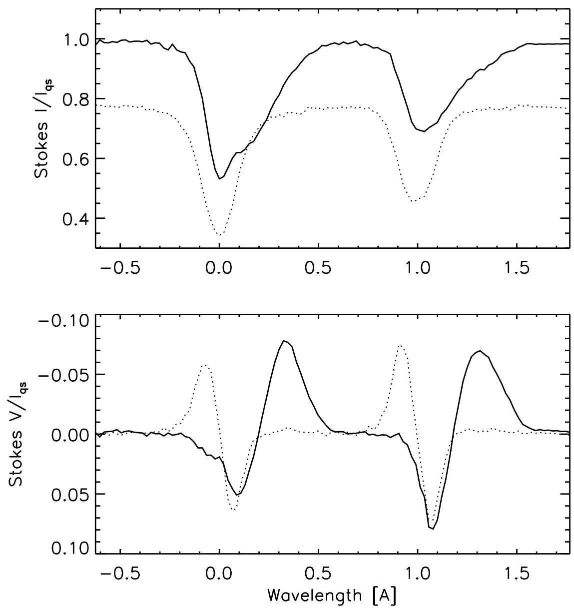

Fig. 2. Stokes I and V profiles observed in one of the downflowing patches of Fig. 1 and a nearby pixel at the same radial distance (*solid* and *dotted* lines, respectively). The exact position of the profiles is indicated in the *right* panel of Fig. 1 with a *circle*. The *dotted* lines represent typical signals in the outer penumbra, with the polarity of the spot and very small flows (the observations were taken close to disk center). The zero of the wavelength scale corresponds to the line-core position of the average quiet Sun intensity profile, computed from pixels with Stokes V amplitudes smaller than 0.5% of the continuum intensity.

The Evershed Flow is Associated with the Weaker and More Inclined Fields of the Penumbra

A well-established observational result is that the Evershed flow happens along the more horizontal fields of the penumbra (see Tritschler 2009 for a review). Indeed, it has been demonstrated that the azimuthally averaged flow is parallel to the magnetic field vector all the way from the inner to the outer penumbra (Bellot Rubio et al. 2003). Near the umbra the inclined fields reside in the bright filaments (e.g., Jurčák et al. 2007), but at larger radial distances they tend to occur in dark structures. It is also accepted that the flow is associated with the weaker fields of the penumbra, except perhaps in the outer penumbra where the strength of the ambient field decreases rapidly (Bellot Rubio et al. 2004; Borrero et al. 2005, 2006; Tritschler et al. 2007; Beck 2008).

For the most part, these results have been obtained from the inversion of spectropolarimetric measurements that do not spatially resolve the different components of the penumbra. Title et al. (1993), Rimmele (1995),

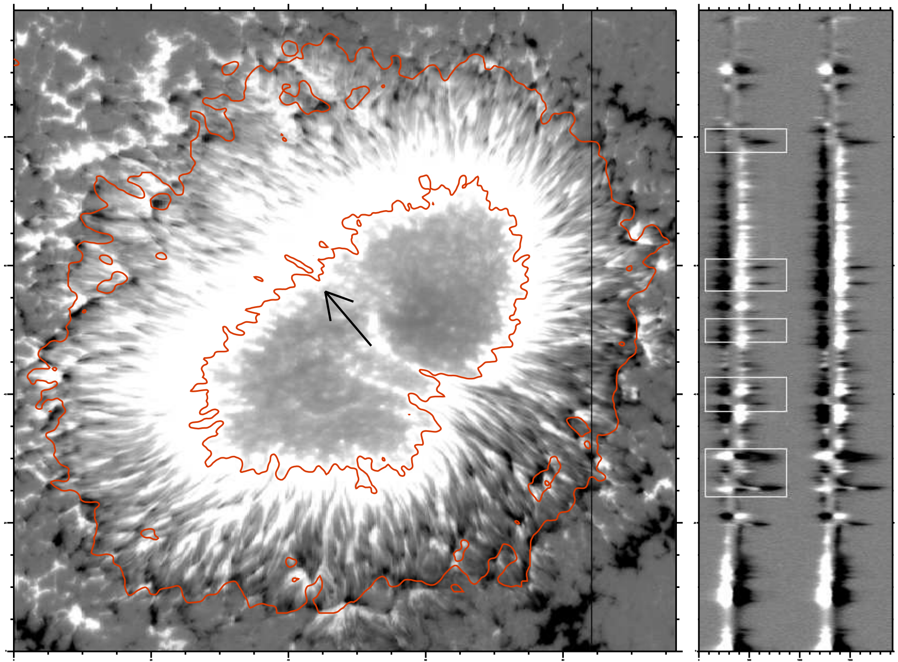

Fig. 3. *Left:* AR 10923 as observed with the Hinode spectropolarimeter on 14 November 2006 between 16:30 and 17:16 UT. The map shows the integral of the Stokes V profile of Fe I 630.25 nm over the red lobe. *Black* and *white* represent opposite magnetic polarities. The *arrow* indicates the direction to disk center. The heliocentric angle of the spot was 8°. *Right:* Circular polarization profiles of Fe I 630.15 and 630.25 nm along the slit indicated in the *left* panel. The *rectangles* show examples of pixels with opposite polarities and very strong Doppler shifts, both at the outer penumbral boundary and well within the penumbra.

Langhans et al. (2005), and others investigated the relation between the flow and the magnetic field using high-resolution magnetograms where penumbral filaments are clearly distinguished, but their results cannot be considered complete because of the lack of linear polarization measurements.

Hinode has allowed us to study the magnetic and dynamic configuration of individual filaments with full Stokes polarimetry and complex atmospheric models. Jurčák et al. (2007), for instance, applied an uncombed model consisting of a single magnetic atmosphere with a flux tube occupying part of the line-forming region. Their inversions provide the variation of the physical parameters with height. Figure 4 shows a vertical cut crossing the inner penumbra of AR 10923 on 10 November 2006. The cut samples four bright penumbral filaments. As can be seen, the Evershed flow occurs deep in the photosphere at the position of the filaments. It is confined to narrow channels having weaker and more inclined fields than the ambient medium. This is the

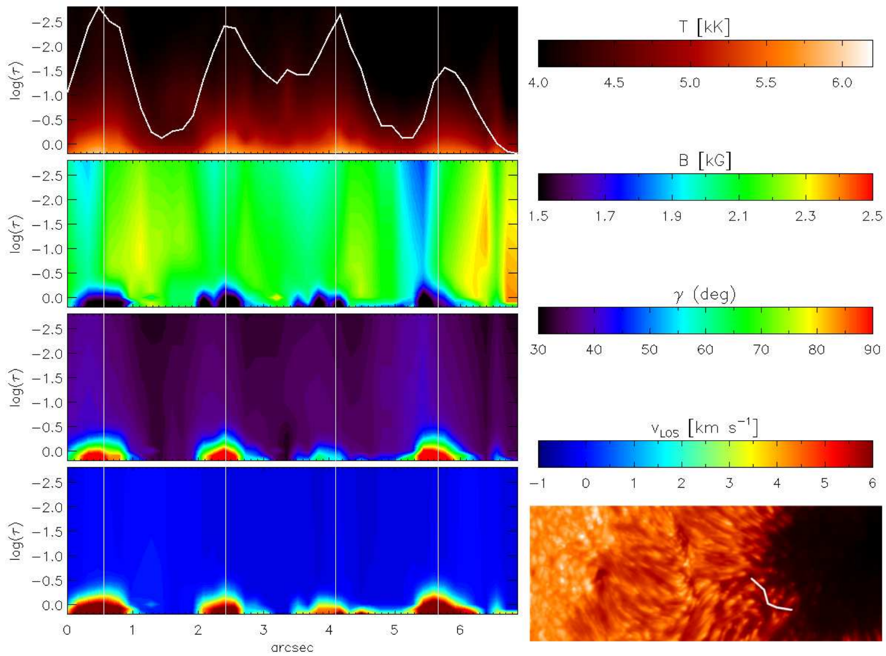

Fig. 4. Vertical stratification of atmospheric parameters along a cut in the inner penumbra of AR 10973 as observed by Hinode on 10 May 2006, at $\theta = 46^{\circ}$. The cut crosses four bright filaments of the limb-side penumbra (*lower right corner* of the figure). The *left* panels show, from *top* to *bottom*, temperature, field strength, field inclination (in the LOS reference frame), and LOS velocity as a function of optical depth, with *color bars* to the *right*. The curve overplotted in the temperature panel represents the continuum intensity along the cut. See Jurčák et al. (2007) for details.

first time that the magnetic and thermodynamic structure of the flow channels is visualized simultaneously in the vertical and horizontal directions with high angular resolution. The results are less clear in the middle and outer penumbra where it becomes difficult to trace individual filaments, but the flow still seems to be associated with the more inclined fields (Jurčák and Bellot Rubio 2008). Similar results have been derived by Borrero et al. (2008) from inversions of Hinode measurements, confirming the overall picture of flow channels embedded in a stronger and more vertical field. As expected, the ambient field wraps around the flow channels, at least in the visible layers of the photosphere (Borrero et al. 2008).

The Evershed Flow is Magnetized

It should be clear by now that the Evershed flow is magnetized, but there are other arguments supporting this conclusion. One of them is the net circular po-

larization (NCP) observed in the penumbra (e.g., Sánchez Almeida and Lites 1992; Martínez Pillet 2000; Westendorp Plaza et al. 2001; Müller et al. 2002; Schlichenmaier and Collados 2002; Tritschler et al. 2007; Ichimoto et al. 2008). Nonzero NCPs can be produced by flows of field-free plasma, as happens, for instance, in the canopy of network and facular magnetic elements. However, this mechanism creates relatively small NCPs; the large values found in sunspots require the flow to occur in a magnetized atmosphere.

Another argument is the existence of strong Doppler shifts in the polarization profiles emerging from the penumbra. The shifts are induced by the Evershed flow, which has to be magnetized to be able to displace the Stokes signals. Figure 2 shows an extreme example: it is just impossible to explain this kind of profiles with field-free flows, because a magnetic field is required to generate the observed polarization signals through the Zeeman effect. The multi-lobed Stokes V profiles occurring all over the penumbra (and not only near the neutral line, as first pointed out by Bellot Rubio et al. 2002) provide more examples of Doppler shifts induced by flows of magnetized plasma. We have mentioned already that they can be interpreted as the superposition of two regular Stokes V profiles, one of which is displaced in wavelength with respect to the other. Only flows occurring in a magnetized environment can shift the polarization signals to the extent required to generate Stokes V spectra with three or more lobes (see, e.g., Fig. 1 of Bellot Rubio 2006).

Borrero & Solanki (2008) inverted Hinode measurements in terms of model atmospheres featuring vertical gradients of the parameters. Their results show that the field strength of structures associated with strong Evershed flows initially decreases with depth in high photospheric layers, but then increases as the continuum forming layers are approached. This behavior is incompatible with the presence of field-free plasma near or just below $\tau = 1$.

The Evershed Flow Continues Beyond the Sunspot Border as MMFs

Cabrera Solana et al. (2006) have shown that some moving magnetic features (MMFs) in the sunspot moat are generated by Evershed clouds, that is, patches of enhanced Evershed flows that move radially outward in the penumbra. Once in the moat, the Evershed clouds exhibit large velocities for some time. These findings support the idea that MMFs come from inside the spot (Sainz Dalda and Martínez Pillet 2005; Ravindra 2006; Kubo et al. 2007) and suggest that the Evershed flow is not caused by small-scale convection in a strong magnetic field, as it is also observed in the relatively field-free environment of the moat.

3 Heating of the Penumbra by the Evershed Flow

In a recent paper, Ruiz Cobo and Bellot Rubio (2008) investigated the ability of the Evershed flow to explain the brightness of the penumbra. To that end

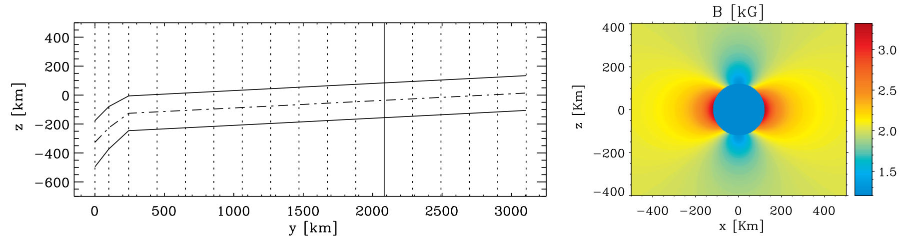

Fig. 5. Magnetic flux tube embedded in a background (umbral-like) atmosphere. The tube has a diameter of 240 km. This configuration is intended to represent bright filaments near the umbra/penumbra boundary. *Left:* Vertical cut in the radial (y) direction. The umbra is to the *left* and the outer penumbra to the *right*. The vertical axis indicates height in the photosphere. $z = 0$ km corresponds to $\tau = 1$. *Right:* Cross-section of the tube. Displayed in color is the distribution of the magnetic field strength. The tube has a weaker field than the background atmosphere. However, the ambient field is potential and therefore it shows strong spatial variations near the tube.

they solved the 2D heat transfer equation in a simple model of a flow channel embedded in a stratified atmosphere (Fig. 5). Consistent with the results described above, the simulated flow is radial, lies deep in the photosphere, and has weaker and more inclined fields than the ambient medium. The flow speed is 7 km s^{-1} at $y = 0$ km, but it becomes supersonic farther out.

The Evershed flow brings hot plasma from subsurface layers into the photosphere, leading to temperature enhancements inside and outside the flow channel. To determine the equilibrium temperature distribution, the stationary heat transfer equation was solved numerically in 17 vertical planes spanning more than 3000 km in the radial direction. The temperatures obtained in this way ensure an exact balance between radiative losses and the energy supplied by the Evershed flow. As can be seen in Fig. 6, the flow induces temperature enhancements of up to 6000 K. In the deepest photospheric layers accessible to the observations, around $\tau = 1$, the temperature of the plasma is increased by nearly 3000 K.

The physical parameters obtained from the calculations were used to synthesize the Stokes profiles of the Fe I 630.25 nm line emerging from the model. The results are presented in Fig. 7. The three panels display a continuum image, a longitudinal magnetogram, and a Dopplergram. In continuum intensity, the flow channel would be observed as a filament with a bright head and a dark core. The lateral brightenings are separated by about 250 km. This filament is very similar to those observed in the inner penumbra and has a length of 3000 km. The most important result, however, is that the Evershed flow heats the surroundings very efficiently: the average brightness in the box is approximately 50% of the quiet Sun value. Without the flow, it would be only 6%, corresponding to a very cool umbra. The average brightness is still

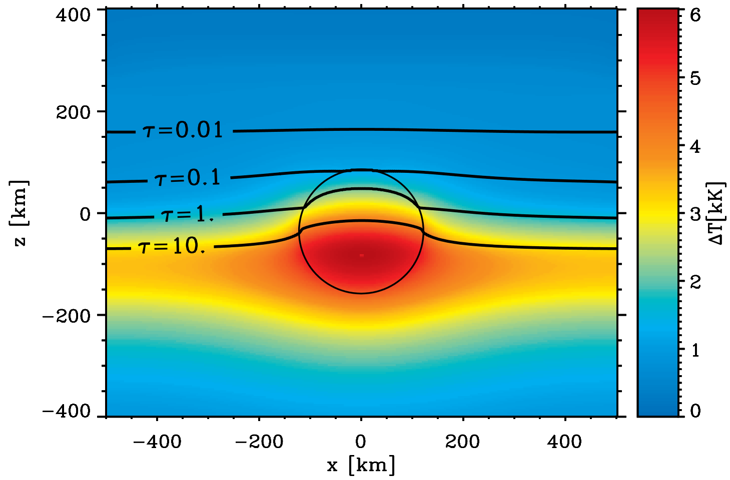

Fig. 6. Temperature perturbations induced by the Evershed flow in the xz-plane at $y = 2083$ km (see Fig. 5). The temperature distribution without the flow is that of the cool umbral model of Collados et al. (1994). The *circle* represents the flow channel. The *solid lines* indicate constant Rosseland optical depths.

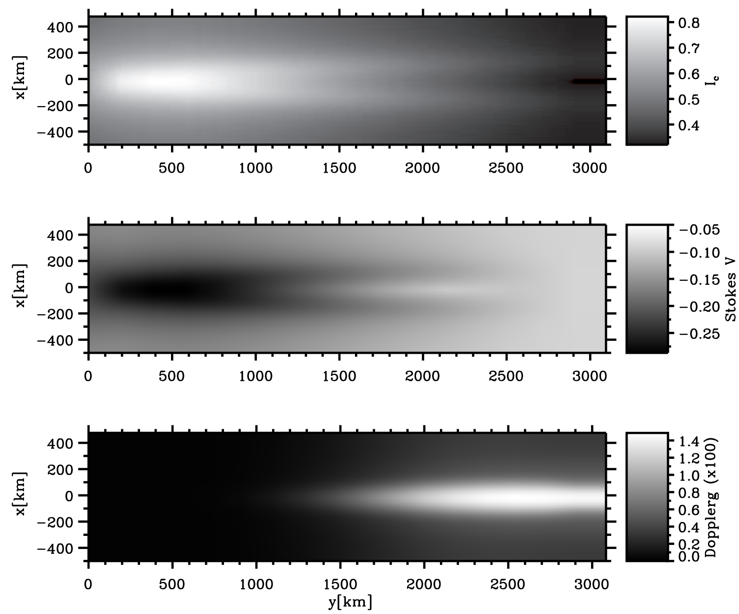

Fig. 7. Magnetic flux tube of Fig. 5 as observed through a 1-m telescope in the Fe I 630.25 nm line. *Top*: Continuum intensity at 630 nm. *Middle:* Stokes V map at +10 pm from line center. *Bottom:* Dopplergram calculated using Stokes I at ±15 pm from line center.

a bit low, but it should be possible to increase it with small changes in the flow velocity and other simulation parameters.

The magnetogram of Fig. 7 shows weaker circular polarization signal in the dark core as compared with the lateral brightenings. This is exactly what is observed (Langhans et al. 2005, 2007; Bellot Rubio et al. 2007; van Noort & Rouppe van der Voort 2008). Moreover, the Dopplergram indicates that the dark core harbors the largest velocities, in agreement with the findings of Bellot Rubio et al. (2005), Langhans et al. (2005), and Rimmele (2008).

A flow channel is capable of heating the atmosphere over a distance of 3000 km (Fig. 7). Therefore, it does not need to return to the solar surface within the short lengths estimated by Schlichenmaier and Solanki (2003). The fundamental difference here is a much longer cooling time due to the fact that, in the stationary phase, the background atmosphere has been heated by the flow and is already hot. Thus, the temperature gradient between the flow channel and the surroundings is smaller than that considered by Schlichenmaier et al. (1999). This leads to longer cooling times and longer filaments.

According to the calculations of Ruiz Cobo and Bellot Rubio (2008), bright penumbral filaments are the manifestation of deep-lying, radial Evershed flows along nearly horizontal field lines. The dark cores are produced by the weaker fields associated with the flows, which increase the opacity and move the $\tau = 1$ surface to higher layers where the temperature is lower. The lateral brightenings represent the walls of the flow channel and their immediate surroundings. Thus, the dark core and the bright edges trace the same physical entity. This explains why they follow parallel trajectories and move with the same speed. The nonzero velocities observed in the bright edges can also be understood in a natural way: they are produced by the Evershed flow, but appear diluted because of the contribution of the ambient medium, which is essentially at rest. The penumbral filaments are deep-lying structures. The fact that the dark cores show up clearly in intensity measurements taken at the center of Zeeman-sensitive lines (e.g., Scharmer et al. 2008) does not imply that they are formed high in the atmosphere. They may appear dark in line-core images simply because they have weaker field strengths (which decreases the separation between the σ-components of the Zeeman pattern) and larger field inclinations (which increases the amplitude of the central π-component). The two effect work in the same direction, reducing the line-core intensity. The weaker and more inclined fields can be located deep in the photosphere and still be able to modify the line-core intensity due to the large width of the contribution functions.

4 Convection in Penumbral Filaments

Spruit and Scharmer (2006) and Scharmer and Spruit (2006) proposed the idea of field-free gaps protruding into the sunspot from below as an alternative mechanism to heat the penumbra. The gaps would be located beneath

the bright penumbral filaments and would sustain overturning convection, carrying energy to the surface and producing the Evershed flow (for a detailed explanation, see the review by Scharmer 2008). Magnetoconvection simulations of sunspots, while still in their infancy, appear to support this picture (Heinemann et al. 2007). The gappy penumbral model is not free from problems, however, and radiative transfer calculations are urgently needed to confront it with spectropolarimetric measurements (Bellot Rubio 2007; Schlichenmaier 2009; Borrero 2009; Thomas 2009).

On the observational side, there have been some claims of the detection of convective flows in the penumbra. Using Hinode filtergrams, Ichimoto et al. (2007b) described a systematic twisting motion of brightness fluctuations in filaments located perpendicularly to the line of symmetry. The motion always occurs from the limb toward the observer, so the twist was interpreted as the manifestation of overturning convection within the filaments. The Doppler measurements of Zakharov et al. (2008) and Rimmele (2008) indicate the existence of weak upflows at the center of penumbral filaments and downflows on their sides. As in normal granular convection, the upflows would turn into downflows after releasing energy in the photosphere. This process of heat transport in the vertical direction would explain the brightness of the penumbra. The observed velocities are of the order of $1\,\mathrm{km\,s^{-1}}$, well below those associated with the Evershed flow. Interestingly, downflows at the periphery of penumbral filaments are also present in the MHD simulations of Rempel et al. (2009), albeit with larger velocities.

The question of whether overturning convection exists in the penumbra is far from settled, however. The best spectroscopic measurements of sunspots reach $0.2''$, but they do not provide evidence for overturning downflows in or around penumbral filaments, neither at disk center nor at heliocentric angles of $\sim 20°$ (Fig. 2 of Bellot Rubio et al. 2005). This is at odds with the observations of Zakharov et al. (2008) and Rimmele (2008). To reach a definite conclusion we need spectroscopic measurements at very high spatial resolution. With $0.1''$ it should be possible to determine the flow field across penumbral filaments, resolving internal fluctuations smaller than the width of the filaments themselves. Hopefully, this kind of observations will be provided soon by instruments like IMaX aboard SUNRISE or CRISP at the Swedish Solar Telescope.

5 Conclusions

The Evershed flow exhibits conspicuous fine structure at high angular resolution. It occurs preferentially in the dark cores of penumbral filaments, at least in the inner penumbra. The flow is magnetized and often supersonic, as demonstrated by the observation of Stokes V profiles shifted by up to $9\,\mathrm{km\,s^{-1}}$. At each radial distance, the flow is associated with the more inclined fields of the penumbra; in the inner penumbra this happens in the bright filaments,

while in the outer penumbra the dark filaments have the largest inclinations. The flow is also associated with weaker fields (except perhaps near the edge of the spot).

High-resolution magnetograms by Hinode show the sources and sinks of the Evershed flow with unprecedented clarity, confirming earlier results from Stokes inversions at lower resolution: on average, the flow points upward in the inner penumbra, then becomes horizontal in the middle penumbra, and finally dives down below the solar surface in the outer penumbra. The Hinode observations reveal tiny patches of upflows concentrated preferentially in the inner penumbra and patches of downflows in the mid and outer penumbra; presumably they correspond to the ends of individual flow channels.

Recent numerical calculations by Ruiz Cobo and Bellot Rubio (2008) have demonstrated that Evershed flows with these properties are capable of heating the penumbra very efficiently, while reproducing many other observational features such as the existence of dark-cored penumbral filaments. This result strongly suggests that the radial Evershed flow is indeed responsible for the brightness of the penumbra.

At the same time, there have been observations of small-scale motions in penumbral filaments that could reflect the existence of overturning convection (Ichimoto et al. 2007b; Zakharov et al. 2008; Rimmele 2008). Convection is an essential ingredient of the field-free gap model proposed by Spruit and Scharmer (2006) and seems to occur also in MHD simulations of sunspots (Rempel et al. 2009). However, other spectroscopic observations at $0.2''$ do not show clear evidence for downflows in filaments near the umbra/penumbra boundary (Bellot Rubio et al. 2005).

It is important to clarify whether or not convection exists in the penumbra. To investigate this issue we need spectroscopic observations at $0.1''$. Narrow lanes of downflows should show up clearly in those measurements. Only then will it be possible to assess the contribution of overturning convection to the brightness of the penumbra and compare it with that of the supersonic Evershed flow. Ultimately, these efforts should reveal the primary mode of energy transport in the penumbra. One possibility is that the two mechanisms operate at the same time. In fact, the strong vertical gradients of temperature observed within the flow channels (Fig. 6) may drive convective motions with upflows at the center of the filaments and downflows along their sides. The gas would not cross the field lines if the transverse component of the field is similar to that displayed in Fig. 1 of Borrero (2007). In any case, the velocities associated with this process have to be small. The superposition of the radial Evershed flow and overturning flows would result in two helical, outward-twisted motions, one on each half of the filament. The hot material would ascend at the center of the flow channel while being displaced radially outward by the dominant Evershed flow, and would descend along the filament edges after releasing its energy in the photosphere. Even in that case, the brightness of the penumbra would still be due to hot upflows channeled by nearly horizontal field lines.

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